Characterization of Dynamic Parameters of a Structure Made Of Spider Silk Dragline

Jorge Alencastre
Jorge Vera Mechan
Pontificia Universidad Católica del Perú

José Luis Muñoz
Javier Echavarri
ETSII-UPM -España

Abstract

The aim of the research was to determine the dynamic parameters of the structure made of spider silk, addressing the topic from an analytical-experimental perspective. The physical structure made of spider silk is meant to copy an original and natural spider web as a special class of prestressed systems called equitensional structures. A conceptual model was developed, composed of silk threads which reach one each other and a point mass at that intersection, which analytically describes in a roughly way, the dynamic behavior of the structure made by the spiders silk gland producer "Major ampullate" (MA). Using free vibration techniques, two experiments were performed. Comparisons between analytical and experimental values obtained show a great coincidence in relation to the natural frequencies of the system, with minor errors than 2% for the fundamental frequency. Intrinsic damping capacities of the structure and silk's viscosity were also determined. Based on the results, it is concluded that the main function of the spider web is to convert the kinetic energy deformation energy and especially dissipative energy, thanks to the silk's viscoelastic properties.

1. Introduction

The term Biomimetics (Agnarsson,I. 2010, Bath Friedrichr, 1988, Blackledge,T., 2009) has become common in scientific issues, and refers to the work of various scientists (engineers, chemist, physicists, biologists, etc.) who try to copy and apply biological processes in different technological and scientific areas. In this scientific field, one of the natural products that are the most striking is the web (Blamires, S. 2012, Cranford, S., 2012, Wu Chao-Chia., 2013, Gosline, J., 1999).A silk fiber Is much stronger than a steel wire of similar thickness, and much more elastic. Simultaneously, the unique molecular structure of the silk fiber can stretch allows up to twenty times its length without breaking. All this in natural, biodegradable and harmless origin material (Gosline,J., 1999, Anita Hoffman. 1993, Ko, F.,2004). Not in vain, man has tried for decades to use this unique material for their technological purposes, attempts that were unsuccessful until recently. The closest artificial equivalent is the Kevlar, a synthetic fiber that its use in the bulletproof vest fabrication, is three times less resistant and much less elasticity than spider silk, it has a high production cost and its manufacturing involves the use of high pressures and temperatures, as well as acids, highly polluting organic solvents (Gosline,J., 1999).

Some research that study the spider web as a special class of system called the equitensional are the pre-tensioned structures (Ko,F., 2004) which have a specific blend of geometry and mechanical properties, resulting in highly efficient structures, due to the optimal distribution of the structural mass. The geometry plays a major role in defending the existence and the rigidity of a structure type equitensional. The claim little changes the stiffness of the structure. However it plays an important role in delaying the onset of loose strings (Lin. Lorraine-. 1995, 1 Montenegro, R., 2005).A damped oscillating system of one freedom degree is propose, as an analytical conceptual model to represent the dynamic behavior of the equitensional structure made of spider silk . The description of the conceptual model generates a nonlinear differential equation of motion , as a result of the inclusion of the intrinsic strength of spider silk threads and the intrinsic damping of the structure made of silk MA (Montenegro , R. , 2005 Sensenig A. , 2013 , Tarakanova , A. , 2012) .

To determine the natural frequencies and vibration diagrams of experimental structure were used free vibrations techniques; on the other hand, for the solution of the differential equation were employed numerical methods.
The results obtained both analytically and experimentally agree qualitatively and quantitatively, thus validating the analytical model proposed to study the dynamic behavior of the structure made of spider silk.

2. Statement of the conceptual Model

The physical system , which will be called 'structure made of silk MA' (security threads) used in the experimental part for determining dynamic parameters, comprises two pre- tensioned MA silks with an initial force " S "which perpendicularly intersect, in that intersecting it is tied to a point mass , formed by a reflective tape and fastened iron filings . The ends of both silks, individually, fixed to a support (pin). The experimental setup of the structure can be represented by a conceptual model as shown in Fig. 1.

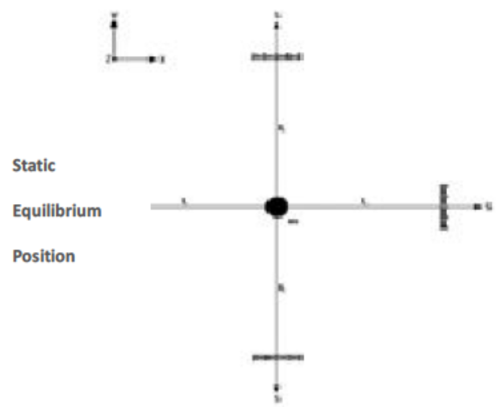

Fig. 1: Conceptual Model

The following analytical model shown in Fig 2.was used to determine the differential equation of motion. Spider silk was considered as a viscoelastic Kelvin- Voigt model type, which shows elements for storing energy (represented by the springs) and the energy dissipation (represented by the dampers)

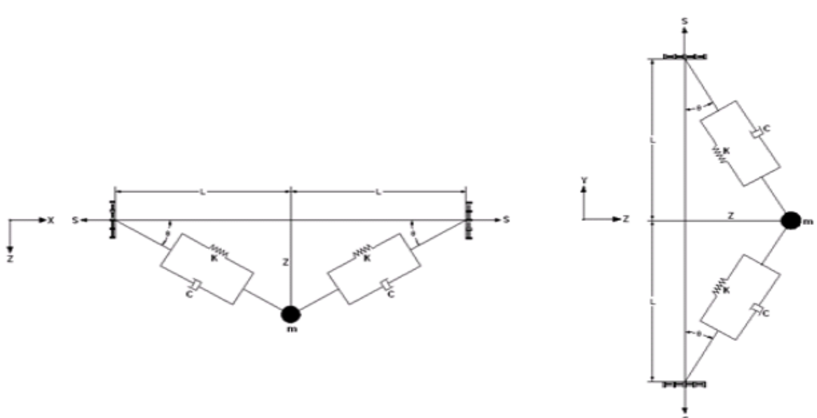

Fig. 2: Displacement "z" in the XZ and YZ planes.

The differential equation describing the dynamic behavior of the system previously shown, under geometrically nonlinear initial conditions, it is described by:

$$\underbrace{m\ddot{z}}_{\substack{Inertial\\Force}} + \underbrace{4C\left(\frac{z^2}{L^2+z^2}\right)\dot{z}}_{\substack{Damping\\Force\\Or\\Dissipative\\Force}} + \underbrace{4S\left(\frac{z}{\sqrt{L^2+z^2}}\right) + \frac{4EA}{L}\left(z - \frac{zL}{\sqrt{L^2+z^2}}\right)}_{\substack{Restorative\\Force}} = 0 \qquad (1)$$

The equation of motion (1) can be replaced by a simplified *McLaurin*'s equation expanding in series.

$$\underbrace{m\ddot{z}}_{\substack{Inertial\\Force}} + \underbrace{\frac{4C}{L^2} z^2 \dot{z}}_{\substack{Dissipative\\Force}} + \underbrace{\frac{4S}{L} z + \frac{2EA}{L^3} z^3}_{\substack{Restorative\\Force}} = 0 \qquad (2)$$

The equation (2) represents a dynamic system damped of free vibration in geometrically nonlinear displacement "z". In this equation the natural frequency depends not only on the parameters within the system but also on the initial conditions. In order to appreciate how to vary the frequency of the system and to apply the method of the disturbance for settlement will be neglected in (2) the term corresponding to the damping force; the result is an expression whose fourth frequency approximation is governed by the following expression:

$$\omega_1^2 = \omega^2 + \frac{3\alpha z^2}{4} - \frac{3\alpha^2 z^4}{128\omega^2} + \frac{9\alpha^3 z^6}{512\omega^4} \qquad (3)$$

In the previous expression it is observed that the frequency of the nonlinear system (ω_1) varies with the amplitude (z), but to find its value, ω y α are required, the latter being a parameter containing "E", module that characterizes stiffness in uniaxial state, of any material and therefore to spider silk.

The approximate solution of the differential equation of motion of the system (1) which considers only the damping of the structure made of silk MA (C),was obtained using numerical methods especially RungeKutta No. 4 for Systems (RK4S).

3. Static trials and vibration

Static to silk and free to the structure made with silk MA (security thread) vibration tests were conducted. In order to limit the variability of the mechanical properties of the silk, the obtention of the MA silk was made during segregation of spider silk made while free climbing (security thread).The determination of the diameters of security threats were made using a Scanning Electron Microscope (SEM) with an average diameter of the wires of approximately 3.5 microns. Free vibration trial under environmental conditions, were performed using a laser speed and signals Multi-Analyser software system version 12.5.0 Press LabShop Brüel & Kjær. The excitation of the system is performed using an electromagnet.

The configuration of the system consists of two silks MA with a length (2) of 10 cm in a position perpendicular (as shown in Fig.1) prestressed with a force "" of 0.0032 N. The value of the prestressing force is obtained after perform various tests that allow the system to be tight enough, besides offering ease of elongate up to the maximum of its elastic range without reaching the break. At the intersection of a point mass both threads of $2.10\text{x}10^{-5}$ kg comprised of a reflective tape and iron filings (Fig. 1) were placed. To start the free vibrations of the system switch adjustable source was operated, he began to energize the electromagnet creating a magnetic field, which served to attract iron filings from the static equilibrium position at a distance of 1.1 cm; plus the initial velocity was 0 m / s. These initial conditions vary silk made initial pretension force "" (0.0032 N) to a restricted its elastic limit, thereby causing the elastic material properties (modulus of elasticity E, silk section A) involved in characterizing the dynamic properties of the system.

When displaced the system, the power supply to the electromagnet is interrupted, the system to oscillate freely to regain the position of static equilibrium. This movement was captured by the laser speed through the reflective tape, located on the reverse side of the iron filings. To carry out dynamic tests under vacuum conditions, he had to use a vacuum chamber and the same equipment as in tests at ambient conditions. The condition of vacuum was 1 mbar.

4. Results

The following figures reveal the results obtained through out experimental and analytic ways. The graphics in figure 3 show the curve of Force-Deformation of one of the multiple trials in traction done to the spiders silk, the same way the trials of load and unload. .

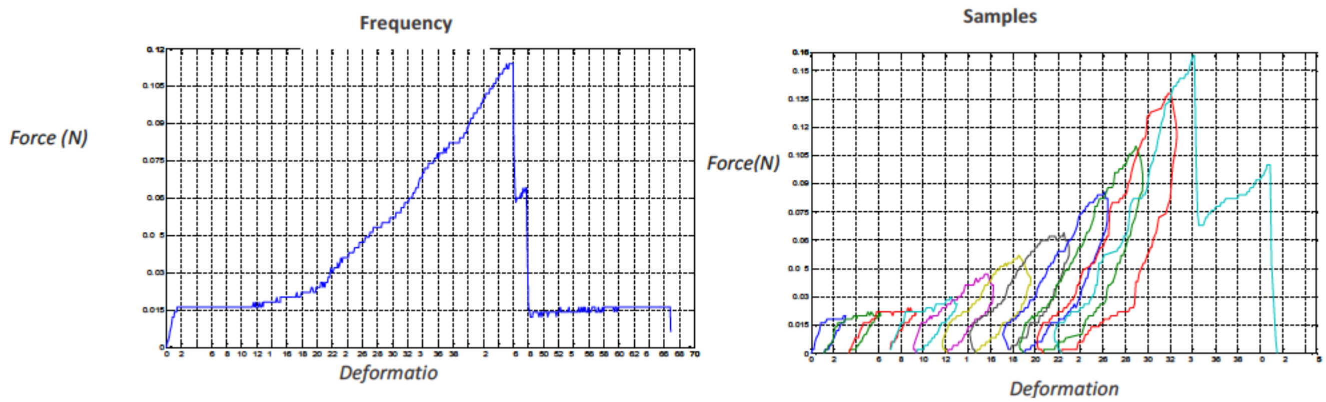

Fig. 3:a) Curve Force-Deformation b) Curve load-unload

Figures 4 and 5 reveal the results of the experimental tests of free vibrations and the ones obtained in the solving of the equation of differential movement.

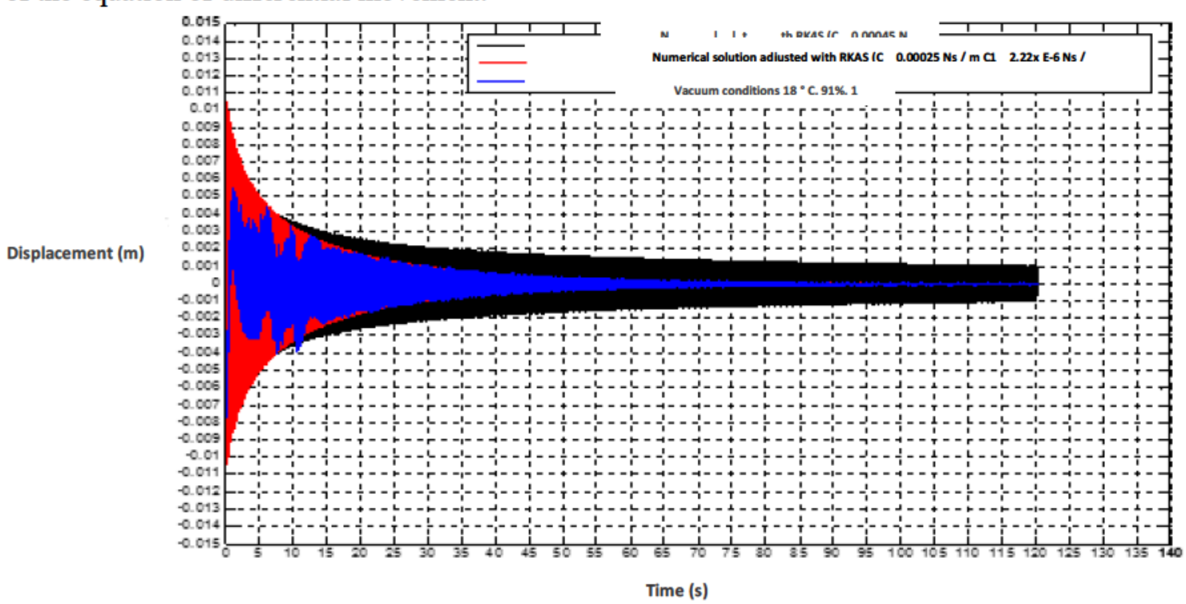

Fig. 4: Analytical and experimental solution

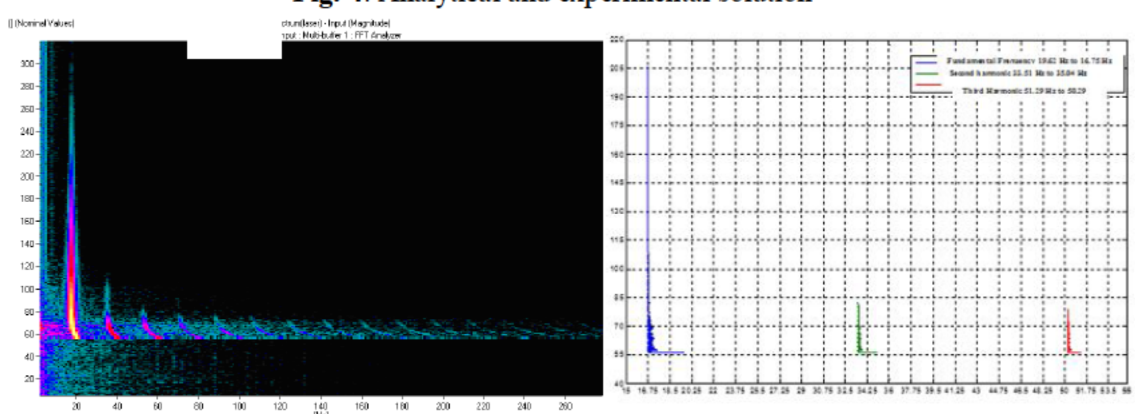

Fig. 5: a) Intensity of autospectrum b) Evolution of the analytical frequency over time

Taking in account that the values of evolution of the frequency tend to a lower value, table 1 is been made.

Table 1: Comparison of the natural frequencies between the results obtained analytically and those obtained from the trials in vacuum condition.

	First Harmonic	Second Harmonic	Third Harmonic
Trials	17.17 Hz	34.44 Hz	52.49 Hz
Analytic	16.75 Hz	33.51 Hz	50. 29 Hz
Error	0.42 Hz	0.93 Hz	2.2 Hz
Error (%)	2.45	2.7	4.2

5. Discussion

Figure 3a shows that the elastic range is found approximately between 0% and 2% of deformity and between 0N and 0.016 N of force; the tendency of the curves is the same when the trials of load and unload are made (Fig. 3b). Additionally, from this curve we can close that when the silk is deformed and loaded farther that 2% and 0.016 N respectively, it shows a permanent deformation, and this behavior infers that the trial of the silk is found between the elastic ranges. From the same figure can be deduced that the silk have a viscoelastic behavior, for showing of hysteresis bonds.

In figure 4 in can be observed the comparison of the results obtained experimentally in vacuum conditions (Blue curve) with the analytic solution with the intrinsic damping value of the structure C=0.00045 Ns/m (Black curve). It is clearly visible that the analytic solution don't retake the position of static equilibrium, leaving a remnant vibration; This behavior is justified, because after the no lineal initial stage, the analytic sister goes to the lineal range, where there is no term that dims the vibration and the system ranges like a pre tensed string with a punctual mass. In the same Figure its shown the analytic system vibrations adjusted with a member that represents the damping of the joints and the low vacuum (Orange curve) that tend rapidly to the experimental solution. The value of said damping is very small, representing 0.8% of the intrinsic damping of the structure, but it is important for the analytic solution to return to a static equilibrium position.

Figure 5 shows that intensity of auto specter (Exe X: Frequency, Axis Y: Samples number, Color: Breadth) for the experimental trials in vacuum conditions and in the fig 5, is appreciable the evolution of the analytic frequency in the time. From table 1 it is deduced that the errors from the frequency are less than 4%. This indicates that the conceptual model that was proposed is adequate to represent correctly the dynamic behavior of the silk made structure MA.

6. Conclusions

The investigation of the behavior of the spider silk made structure MA, turns itself in a first approximation to be able to understand and evaluate the dynamic behavior of a spider's web as a structure of equitensional type. The analysis techniques of free vibrations as a method to quantify the dynamic properties of the system have given satisfying results. The study of the free vibration of the structure made of silk MA in the nonlinear range has allowed, as a first approximation, determinate the dynamic parameters of the silk made structure MA, natural frequency and damping coefficient.

The evaluations of the analytic and experimental results reflect clearly in the principal function of the spiders silk is to turn kinetic energy in deformity energy, and primarily in dissipation energy, fact that is affected because of the viscoelastic properties of the silk. The intrinsic damping coefficient of the structure is very small, but the spiders apparently resorts to the help of the air (as dissipater element) for the good functioning of the spiders web at the moment of capturing their prey, dissipating the 99% of the total energy in the first three cycles of oscillation of the spiders silks at the impact of the prey.

Using the conceptual model of a pre-tensed string with a punctual mass is adequate to represent correctly the dynamic behavior of the structure made in silk MA. To represent the silk MA like a mechanic model of Kelvin-Voigt, to evaluate its properties of storage and dissipation have been coherent and has allowed us said properties.

References

Agnarsson,I., Kuntner, M, Blackledge,T. *Bioprospecting Finds the Toughest Biological Material: Extraordinary Silk from a Giant Riverine Orb Spider*. The Toughest Biomaterial, Vol. 5 (2010), 1-8.

Bath Friedrichr. Vibration and spider behavior. XI. Europäisches Arachnologisches Colloquim, 1988.

Blackledge,T., Nikolaj Scharff, Jonathan A. Coddington, Tamas Szüts, John W. Wenzel, Cheryl Y. Hayashi and Ingi Agnarsson. Reconstructing web evolution and spider diversification in the molecular era. PNAS 2009, Vol16. 5229-5234.

Blamires, S,Chung-Lin Wu, Blackledge, T, I-Min Tso, Post-secretion processing influences spider silk performance *J. R. Soc. Interface October 7, 2012 9 75 2479-2487*

Cranford,S., Tarakanova, A, Pugno, N., Buehler, M. Nonlinear material behavior of spider silk yields robust webs. Nature, Vol. 482 (2012), 72-76.

Chao-Chia Wu., Sean J. Blamires, Chung-Lin Wu, I-Min Tso, Wind induces variations in spider web geometry and sticky spiral droplet volume *Journal of Experimental Biology 2013 216:3342-3349.*

Gosline, J., Guerette, P., Ortelepp, C., and Savage, K., "The Mechanical Design of Spider Silks: From Fibroin Sequence to Mechanical Function", The Journal of Experimental Biology, 202, 1999, 3295-3303.

Hoffmann Anita, "El Maravilloso Mundo de los Arácnidos", Fondo de Cultura Económica, S.A. de C.V., México, 1993. (Book in Spanish)

Ko, Frank K., Jovicic, Jovan. "Modelling of mechanical properties and structural design of spider web". *Biomacromolecules 5 (2004), 780-785.*

Lin.Lorraine., Edmonds,D., Volrath, F. Structural engineering of an orb-spider web. Nature, Vol. 373 (1995), 146-148.

Montenegro, Rivelino."La asombrosa telaraña". *Ciencia de los orígenes N.66, 2003.*(Book in Spanish)

Pérez Rigueiro,J. M. Elices y G.V: Guinea. "Estrategias de la naturaleza en el diseño de materiales: La Seda de Araña" *Biblioteca en línea del Grupo Ibérico de Aracnología, Sociedad Entomológica Aragonesa, 2002.*(Book in Spanish)

Sensenig A., Kimberly A. Lorentz, Sean P. Kelly and Todd A. Blackledge. Spider orb webs rely on radial threads to absorb prey kinetic*J R Soc Interface 2012 9 (73)1880-1891.*

Tarakanova,A, Buehler, M. The role of capture spiral silk properties in the diversification of orb webs *J. R. Soc. Interface December 7, 2012 9 77 .*

Vollrath, F., "Strength and Structure of Spider´s Silks", Molecular Biotechnology, 74, 2000, 67-83.

.